Symmetry Elements Embodied by Students' Hands: Systematically Characterizing and Analyzing Gestures in Inorganic Chemistry

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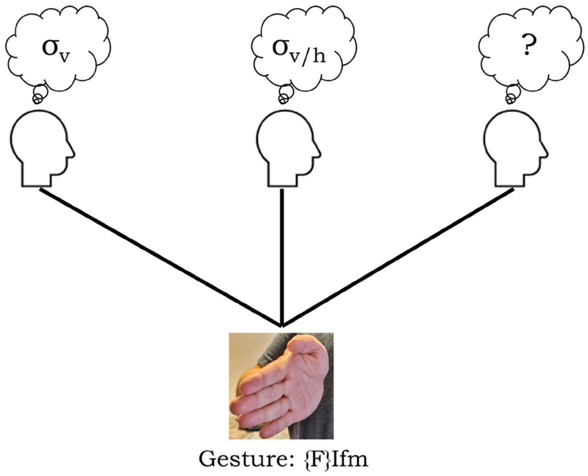
ABSTRACT

We previously observed students gesturing during a symmetry and group theory activity. This prompted additional interviews wherein we attempted to understand the semiotic function of these gestures. We report here on the gestures which students have used in this context to represent symmetry elements, symmetry operations, and other related ideas. In the process, we have developed a scheme to code gestures in a systematic way that enables qualitative analysis and may lend itself to quantitative methods. This analysis leads to two observables: physical forms and motions enacted while representing or thinking about symmetry. These gestures are metaphorical and allow us to infer cognitive notions underlying the gesture as part of the student's reasoning, their communication, or both. Characterizing these gestures and associated notions offers the opportunity to add to our understanding of how gesture and other embodied representations can systematically support student learning in relation to spatial concepts and descriptions in chemistry. This characterization also has implications for instruction to support student learning about symmetry in inorganic chemistry.

GRAPHICAL ABSTRACT



KEYWORDS

Upper-Division Undergraduate; Inorganic Chemistry; Analogies / Transfer; Hands-on Learning / Manipulatives; Group Theory / Symmetry; Chemical Education Research

INTRODUCTION

What topics commonly appear in inorganic chemistry curricula has changed significantly over the past century.[1,2,3,4,5] However, symmetry and group theory is one topic that continues to be widely covered in inorganic chemistry curricula.[6,7,8,9,10,11,12,13] Publications involving symmetry and group theory, which largely focus on in-classroom activities, suggest that this topic is uniquely challenging for students. Several publications describe students struggling with observing certain symmetry elements[7,14,15] determining point groups,[14,16] or using general visualization skills.[12,16,17,18]

In response to these difficulties, researchers detailed how using certain pedagogical approaches[10,11,19], 3D models[14,18], or other tools[9,17,20] can help students become adept at skills relevant to symmetry and group theory. In our own published activity using concrete models and other frameworks to accomplish this same goal[13], we noted students additionally using gesture when engaging with symmetry and group theory. In the process, our observation of students showed that, in addition to analyzing 2D representations, building models, and drawing, students used gestures with their hands as part of their communication and, possibly, reasoning about symmetry. This prompted us to examine the role of gesture more rigorously, drawing on frameworks of embodied cognition in general and with gesture specifically.

LITERATURE FRAMEWORKS

Embodied Cognition

Our work draws on the framework of embodied cognition, which has been used in education research in chemistry[21,22], physics[23,24], and mathematics.[25] The central premise of embodied cognition is that learning and thinking about the world "… is grounded in the interactions our bodies… have with the world around us."[26] Since gestures are manifestations of embodied cognition, we can glean information about student cognition by examining how they use gesture during reasoning and communication tasks about symmetry and group theory in inorganic chemistry.

Gesture in cognition and in chemistry

We consider gestures as manipulations of the body that can be interpreted as utterances in discourse.[26,27,28] Just as an individual can respond to a question in verbal or written modes and signed language[29], one's hands, facial expressions, and other manipulations of the body can serve as nonverbal forms of communication. Flood and coworkers have previously explored the semiotic and communicative use of gesture in a general chemistry setting.[21] Notably, students used gestures to communicate notions that were otherwise cumbersome to elucidate verbally, *e.g.*, the spatial arrangement of atoms in a trigonal bipyramidal compound, and when constructing meaning by themselves and with others.

Considerable research also shows the role gesture has in reasoning and cognition.[26,30,31] In chemistry education research, there has been effort focused on gesture and problem-solving tasks in organic chemistry. For example, Ping and coworkers examined how students used gesture when mentally manipulating stereoisomers[32], and generating a given compound's stereoisomer (if one existed).[22] Stieff, Lira, and Scopelitis demonstrated that gesture can support students when tasked with translating between Newman, Fischer, and dash-wedge representations comparable to using a model kit.[30]

Our work examines gestures in an inorganic chemistry context as participants reason about symmetry and group theory. With considerable literature support of gesture's relation to reasoning and cognition, especially with spatial tasks, we sought to investigate what meaning students ascribed to their gestures. To accomplish this, we have developed a scheme to succinctly but comprehensively code individual gestures so that we might not only ascertain what gestures are most used but also the notions these gestures convey.

Wakefield and Goldin-Meadow[26] described gestures as movements, specifically of the hands, that convey some kind of meaning, either conceptual, referential, or emphatic. This definition distinguishes gestures from movements that serve an explicitly practical purpose.[27] We focus here on gestures that convey conceptual meaning related to symmetry and group theory. These are distinct from gestures that serve a pointing (deictic) or beat purpose.

Following a popular view in the gesture studies community[28,29], Calbris treated representational gestures as signs motivated by a physico-semantic link to a concept or object that the gesture represents. In this manner, gesture serves a role as a non-verbal **metaphor**. She explicitly viewed this class of gesture as metaphorical in that "… using contemporary terms, a representational gesture is established by mapping from a source domain (physical experience) to a target domain (notion)."[33] In other words, one could come to know more about a concept through meaningful bodily motions, *i.e.*, through gesture.

This view of gesture relates to other studies which examined the role of metaphor and analogical reasoning in chemistry. The target domain and source domain dichotomy is established in chemistry education research[34,35,36,37,38,39], and education research more broadly.[40,41,42] The source domain is sometimes referred to as the analog domain when working specifically with analogies[43,44], though the source and target dichotomy otherwise remains. Relevant to our work, we found one instance where bodily involvement in analogy was mentioned[45], though neither those authors nor do we describe that bodily involvement as gesture. What is novel in our approach is the application of the source/target domain frame specifically to gestures in a chemistry setting, as well as the scheme by which we systematically describe **gestural forms**. Following Calbris' stance and others'[36], we also classified the concept or object to which we infer a gesture is referring as a **notion**.

With these frameworks, gesture consists of two components: First, the **gestural form** that can be observed, which includes the **physical form** or **motion** enacted by the hands. Second, these relate to the cognitive **notion(s)** that are conveyed by the speaker and inferred by the observer. By treating the form a gesture takes (the source domain) as a separate construct from the notion we infer (the target domain), we can make relational claims between them and analyze how particular gestural forms act as metaphors that express underlying cognition. The relationship between gestures, gestural form, and notions are described in Figure 1.

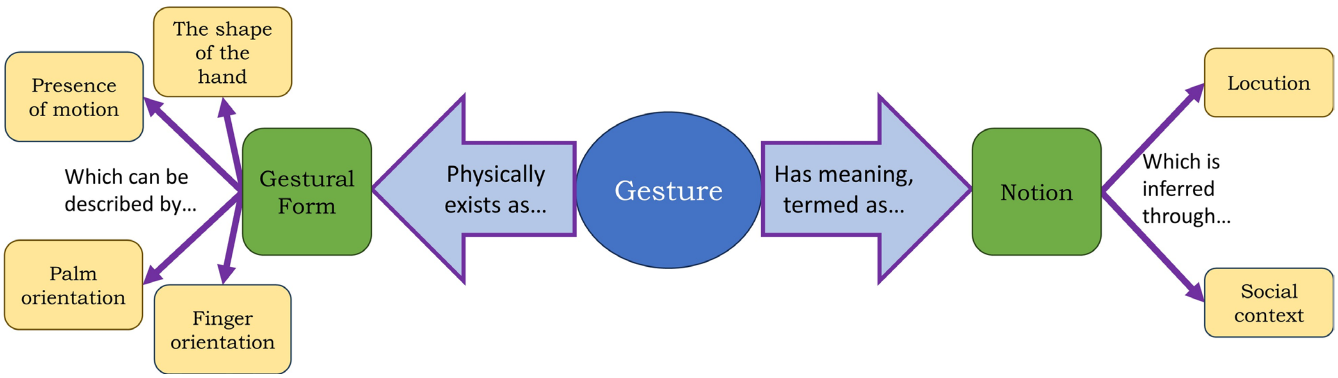


Figure 1. Gesture has two key components. The gestural form is the physical manipulation of the body (or in our framework, specifically of the hand). The notion is the meaning which is being conveyed by that physical manipulation in a particular context.

RESEARCH QUESTIONS

This work was motivated by observations of students completing an activity in a prior publication by the authors.[13] In that work, students gestured frequently and with similar gestural forms despite having no explicit prompt to gesture. Inspired by these observations, and the literature that supports gesture as having cognitive and communicative utility, we proposed the following research questions:

1. What gestural forms are inorganic chemistry students employing as they explore symmetry and group theory?
2. Are there certain notions which are typically associated with certain gestural components?

To address these questions, we examined video data from one-on-one interviews with inorganic chemistry students. We then systematically coded the gestural forms students used and the notions we inferred to identify when these constructs temporally aligned. Finally, we looked for patterns in the components of gestural forms individual students used and tabulated the critical gestural components used across all students for our notions of interest. We hope our work can guide further chemistry education research in this modality and inform pedagogical practice.

METHODS

This study took place in the Midwest United States at a large, federally designated Hispanic-serving urban research university. Participants were recruited from the only undergraduate inorganic chemistry course the institution offers, in both the Fall 2022 and Spring 2023 semesters. Approximately 60-70 students take the course each semester, and most are third-year students. The instructor for the course rotates among the institution's inorganic faculty each semester. The Fall 2022 and Spring 2023 offerings of the course had different instructors. While both instructors used gestures during their lectures, they did not call out that the gestures themselves were to be followed. Instructor gestures were outside of the scope of our data collection protocols and as such were not included in our analysis. All offerings of the course include three fifty-minute lectures by a faculty member and a laboratory section led by a Graduate Teaching Assistant (TA) each week. Symmetry and group theory was covered first in the lecture and then in the laboratory portion of the course, using the activity we have previously described[13].

This study analyzed one-on-one interviews with students after they had completed the laboratory activity. Interviews occurred two to nine weeks after completion of the activity. Consent procedures and interview protocols were approved by the university's Institutional Review Board (ID: 2021−1273). Consenting students were assigned an alphanumeric identifier to protect their identities and compensated with $25 for their time.

Interviews were conducted in Fall 2022 and Spring 2023. Interviews took place in person and outside of regular class hours. The interview format was semi-structured and included 6 phases (see Supporting Information for the protocol). The first phase reiterated the purpose of the interview and asked the interviewee if they still provided consent. Phase two probed the interviewee's familiarity with symmetry operations. We then asked the interviewees in phase three to identify symmetry elements for four compounds. In this phase, pre-constructed molecular models were provided for two of the four compounds. Interviewees were freely gesturing throughout the first three phases. The fourth phase had the interviewer mimic some of the gestures produced by the interviewee and ask about the meaning and origin of those gestures. The fifth phase had the interviewer produce gestures from a list and ask the interviewee to interpret those gestures. Interviewees were encouraged that there were no wrong interpretations and that a gesture having no meaning to them was acceptable. The sixth phase gave room for the interviewee to share any final thoughts before departing.

Interviews in Fall 2022 were recorded on a tripod-mounted video camera, while interviews in Spring 2023 were recorded both on a tripod-mounted video camera and by a webcam on the first author's laptop. In total, seven interviews were analyzed. Two of these interviews were conducted in Fall 2022 (participants Fa1 and Fa2) while the remaining five were conducted in Spring 2023 (participants Sp1 through Sp5).

Coding Referential Gestures Based on their Physical Components

To answer our research questions, we needed a systematic way to describe observed gestures. Other authors in the field of gesture studies developed schema and discussed how they classify gestures.[27, 28, 46, 47] But to our knowledge there are no schemas that relate to the question of molecular structure or symmetry elements, nor that succinctly and systematically describe gestures. Most schema describe gestural forms with full sentences in a narrative fashion[27, 28], though sometimes these are partially abbreviated.[46] We initially developed a similar coding scheme that explicitly described gestural forms in a semi-narrative fashion (*e.g.*, "Point with Index Finger"). Unfortunately, this scheme quickly became unwieldy for anything beyond the simplest gestural forms. Instead, we moved to a form of symbolic notation that indicated if a gesture was of a static physical form or was associated with motion, inspired by Calbris' methodology.[33] We also developed a way to describe components of the gestural form, such as the orientation of the palm or fingers or the type and direction of motion in the case of gestures which included motion. This scheme uses the anatomical planes and axes of the body in Figure 2 for clarity and uniformity.

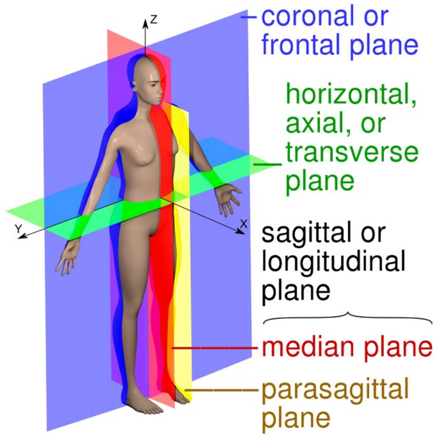


Figure 2. Anatomical planes and axes of the body. Image created by David Richfield, Mikael Häggström, M.D. and CMG Lee. Reproduced with permission, CC BY-SA 4.0.[48]

Following Calbris[33], our coding scheme captures all the relevant physical details of a gestural form in a single code rather than having distinct codes for individual components of a gestural form (*i.e.*, hand shape, orientation, etc.). We categorized gestural forms in a hierarchical fashion based on if they embodied notions purely through gestural form ("F" or form-dependent gestures), or if there was also a movement component ("M" or motion-dependent gestures). Our coding scheme is described in Figure 3.

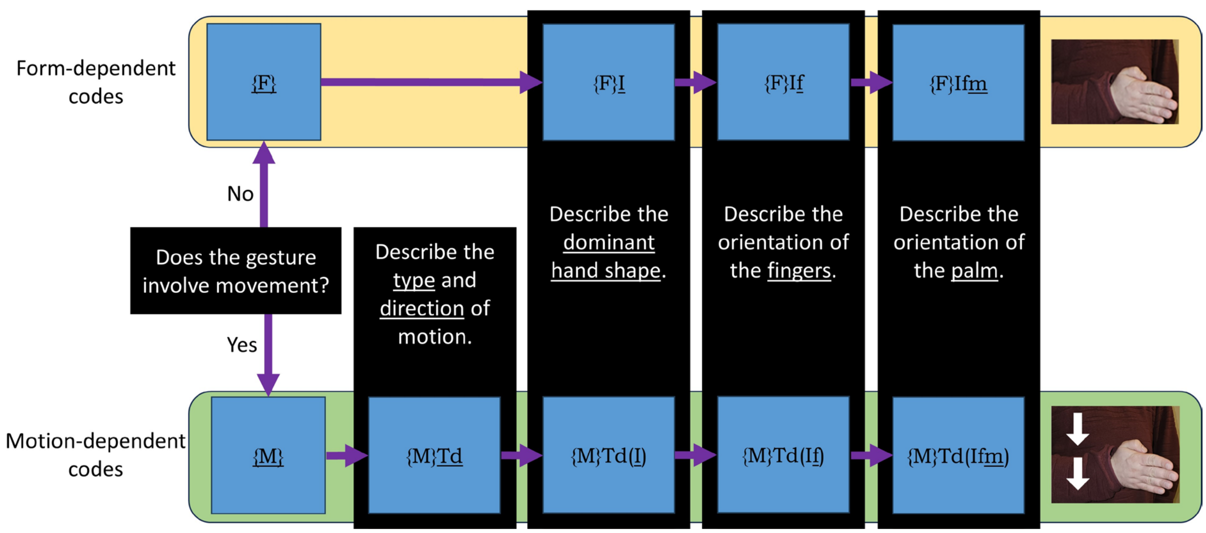


Figure 3. Hierarchal description of gestures with syntax.

Form-Dependent Gesture Code Syntax

Gestures that conveyed notions purely through their gestural form were described as *form-dependent gestures*. We used a base four-letter code for these gestures with the following syntax:

$$\{F\}Abc$$

Where "{F}" simply indicates this as a form-dependent code, "A" indicates the hand shape, "b" describes the orientation of the fingers with respect to the planes and axes of the body, and "c" describes the orientation of the palm.

Figure 4 illustrates this scheme. In this and other gesture photos, we have recreated our participants' original gestures with a new photograph for clarity. The original photos are shown for comparison in Table S4 of the Supporting Information. Without our scheme, this gesture may be described as "a hand oriented parallel to the midsagittal plane of the body with all fingers pointed forward and the palm facing the midsagittal plane." While this form can be thoroughly described in those 23 words, it would be very time-consuming to similarly describe all 218 unique gestural forms we observed in our data.

Figure 4. **Form-dependent ({F})** gesture that was produced by Participant Sp3, with a flat hand oriented here parallel to the midsagittal plane **(I)**, fingers pointed forward **(f)**, and palm faced medially **(m)**. This is coded as {F}Ifm.

With our scheme, the form of this gesture is coded as {F}Ifm. The "{F}" designation indicates that this gesture does not involve movement. The "I" hand shape code, borrowed from Calbris' designation for the same shape, indicates a flat-hand shape oriented in a non-specific vertical fashion (*i.e.*, *not* parallel to the transverse body plane). The third letter, "f", indicates the fingers are faced forward, while the last letter, "m", indicates the palm is faced medially. In this way, we described the physical form of a gesture in 6 characters as opposed to 23 words.

Motion-Dependent Gesture Code Syntax

Gestures perceived as having a critical movement component are *motion-dependent gestures* and use the following syntax:

$$\{M\}De(Abc)$$

Where "{M}" indicates this as a motion-dependent code, "D" indicates the type of motion involved (translational or rotational), and "e" further specifies the direction of the motion. The hand shape component ("A") and orientation components ("b" and "c") from the form-dependent gesture syntax are also utilized for motion-dependent gestures but are placed in a parenthetical to better distinguish them from the characters specifying the type and direction of motion.

Figure 5 shows the first author recreating a motion-dependent gesture produced by participant Sp1. Throughout the duration of the movement, the hand shape and orientation are constant. In our scheme, this would be coded as {M}Td(Imb) as the gestural form has a clear and deliberate motion component ("{M}") wherein the hand translates ("T") downward ("d"). The hand shape is a vertically oriented flat hand ("I") with the fingers oriented towards the medial body plane ("m") and the palm facing back towards the gesturer ("b").

Figure 5. Motion-dependent ({M}) gesture that was produced by Participant Sp1, where the hand translates downward **(Td)**. The hand's shape is flat and parallel to the coronal plane **(I)** with fingers pointed medially **(m)** and palm faced back **(b)**. This is coded as {M}Td(Imb).

Our scheme also accommodates cases where the hand changes shape or where both hands are involved. If both hands are used for a single gesture, the hands are described separately within parentheticals with the left hand being described first. This also allows for the appendment of a motion code in front of the parentheticals in case one (or both) hands move throughout the gesture. If the motion, shape and/or orientation of the hand changes during the gesture, the greater-than symbol (">") is used to separate the codes which describe the initial and final states of the gestural form. A list of abbreviations used in the coding scheme syntax is provided in the Supporting Information.

Student Actions Beyond Gestures

Some students communicated in modes beyond locution and gesture. Occasionally, participants used objects when discussing relevant concepts, such as pens to model axes, notecards as analogues to mirror planes, and rotations of molecular models to communicate a specific rotation operation. Though we might learn much about the participants' thought processes, we elected to restrict our analysis only to the performed gestures as defined in our frameworks. Additionally, students performed deictic gestures, which point to a referent that is not represented by the hand itself. These were also not examined in our study.

Establishing Relationships Between Gestural Forms and Notions

We began this investigation intending to make relational claims between gestural forms and notions as has been done elsewhere.[27, 33] We took as evidence the temporal overlap between an expressed notion and a gestural form as a correlation between them.

The frequency of overlaps between gestural form and notions codes were tabulated for each individual. For sufficiently populated notions of interest, we then looked for patterns not in the entire gestural form, but in the *components* of the gestural form associated with that notion. By observing patterns across individuals, we can make claims that certain gestural components typically convey certain notions in this local environment. Note that we did not expect (nor does the data suggest) that there exists a one-to-one unique relationship between just one gestural form and one notion. But it is the case that certain gestural components, such as specific hand shapes or orientations, were more commonly associated with certain notions.

DATA ANALYSIS

Coding Interview Videos for Gestural Forms

All interviews were transcribed with timestamps and coded for gestural forms and notions in MaxQDA 20.4.2. Codes were created as new gestural forms were documented. In total, 218 unique gestural forms were observed across the seven coded interviews (see Supporting Information). The frequency at which gestural forms were enacted was tabulated to address Research Question 1, which asked what gestural forms were being used by inorganic chemistry students as they explored symmetry and group theory.

Coding Interview Videos for Notions

We began coding notions based on patterns observed in the transcription process as participant locution was a major evidence source for this component of our coding. We developed codes distinguishing rotational symmetry operations (“C2”, “C3”), rotational symmetry elements (“Principal Axis of Rotation”, “Axis”), and beyond. These included codes such as: “Inversion”, “Improper Rotation”, “Mirror Plane”, and the specific mirror planes “Vertical”, “Horizontal”, and “Dihedral”. We also observed notions describing qualities of symmetry elements such as specific rotation angles, motions embodied by operations (“Flipping”, “Folding”, “Translational motion”), and even notions describing the molecular entity under examination (“Straight object”, “H_2O”). Our data contained instances of gestures alongside verbal utterances describing the “flatness” of planes and planar molecules, the “flipping” of objects undergoing rotations, or objects being “cut” when discussing mirror planes. Thus, our notion codebook includes a range of codes that broadly encompasses how our participants reason about symmetry and group theory. By the end of the coding process, we had generated a total of 51 notion codes. The full notion codebook is provided in the Supporting Information.

Notions were coded predominantly based on participant locution and social context. Participant locution was used as evidence whether unprompted or in response to our dialogue. For example, when participant Sp1 was given a molecular model of benzene and prompted to identify symmetry elements, she flattened her hand parallel to the transverse body plane with her palm faced down and fingers faced medially while moving her hand forward, away from her (coded as {M}Tf(Hmd) (see Figure 6, left). She simultaneously stated, “It’s just very flat, and so that’s where you get your horizontal mirror.” She next raised a finger up through the middle of the model (palm faced medially, coded as {F}2um) (see Figure 6, right) while stating that, “The principal axis is actually straight through here.” In this example, the time frame in which the first gesture occurred had notion codes for “Flatness” and “Horizontal”. The second gesture’s time frame had a “Principal Axis” notion code. Instances where the participants gestured with little to no locution could still receive notion codes based on context.

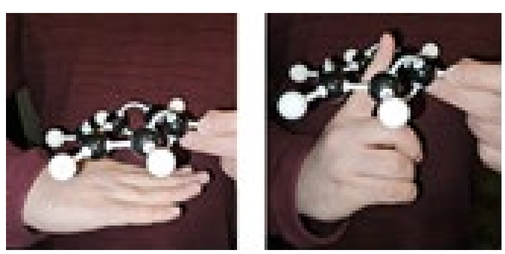


Figure 6. (Left) A gesture that was produced by Participant Sp1 where the hand is parallel to the transverse plane of the body (“H”), with fingers faced towards the midsagittal plane (“m”) and palm faced downward (“d”). The motion would start close to the body and move linearly away in the +x direction ({M}Tf). This gestural form is coded as {M}Tf(Hmd). (Right) A gesture that was produced by Participant Sp1, the model is held with the left hand while the right hand gestures. The gestural form, coded as {F}2um, has the second finger (“2”) pointed upward (“u”) while the palm is faced roughly medially (“m”). There is no significant motion during the gesture.

Eliminating Notions from Final Analysis

We ultimately arrived at 51 notion codes and 829 gestural form-notion overlaps. We removed 29 notions based on two criteria to obtain a list of 22 notion codes. First, some notions were too far removed from symmetry and group theory and instead described notions more closely related to spatial reasoning (*e.g.*, “Origin (Cartesian)”), the entities which we analyze with symmetry and group theory (*e.g.*, “H_2O”, “2D Object”) or motion and orientations (*e.g.*, “Translational motion”, “Upward, up”). Second, other notions, like “Reflection (Operation)” and the three codes for planes described by pairs of cartesian axes (*e.g.*, “XY Plane”), were comparatively undersampled. As our analysis relied on finding patterns across gestures with the same notion, undersampled notions could prove problematic. To keep a notion code, we required a minimum of 3 gestural form-notion overlaps for at least 3 individuals (with the sole exception of notions related to improper rotations, see Results). Finally, we determined some notions to be sufficiently similar and elected to combine them. Notions which we did not deem appropriate to combine and were undersampled were eliminated from further analysis.

The 22 remaining codes were further grouped into 10 notions for analysis, with 4 of these being composites of similar notions. The final set of 10 notions still account for 590 gestural form-notion overlaps, or 71% of the original data set. The six singular notions, or those notions which are not composites of other notions, are: Inversion, Principal Axis, Rotation, Dihedral, Horizontal, and Vertical. The other four notions (Mirror Plane, Proper Rotation, Axis, Improper Rotation) are composites of several notions; we refer to these composites as parent notions, while the individual component notions are referred to as sub-notions. For example, the sub-notions of C_2, C_3, C_4, and C_n were judged as sufficiently similar and grouped into the Proper Rotation parent notion. The six singular notions and four parent notions constitute our main analytical framework and are listed alongside descriptions of the notions in Table 1. The full set of 22 notions, including the grouping of sub-notions into parent notions, is documented in the Supporting Information.

Table 1. Ten Notions Composing Analytical Framework.

Notion codes	Description
Inversion	Movement of an object(s) through a central point.
Principal axis	The axis which allows for the largest rotation.
Rotation	Generic code for movement in a radial manner.
Dihedral	Mirror plane coincident with the principal axis and C_2'' (if present)

Horizontal	Mirror plane perpendicular to the principal axis
Vertical	Mirror plane coincident with the principal axis and C_2' (if present)
Mirror plane (parent code)	Generic code for mirror planes with *no specification* of type
Proper Rotation (parent code)	Rotation that is specifically in line with a proper rotation axis
Axis (parent code)	Generic code for a one-dimensional object (about which rotation *may* occur)
Improper rotation (parent code)	Operation consisting of a rotation and a mirror perpendicular to that axis

Extracting Critical Gestural Components from Gestural Form-Notion Correlations

With the final set of notions determined, we extracted key physical feature(s) of gestures that overlapped with these notions to address Research Question 2, where we inquired as to possible relations between certain notions and certain gestural components. We did this by examining heat maps showing the number of instances in which a participant enacted a gestural form that had temporal overlap with a given notion. Table 2 is an abridged frequency table for participant Sp1 which only includes gestural forms that conveyed the "Mirror plane" parent notion code (among other notions). Full gestural form-notion heat maps for all participants can be found in the Supporting Information. The frequency table here shows the significant breadth of participant Sp1's gestures, with some notions highlighting several gestural variants, or different gestural forms referring to the same notion (*e.g.*, {F}Hfd, {F}Ium, and {M}Td(Ifm) all communicating "Mirror Plane", see Figure 7). Additionally, certain gestural forms exhibited polysemy, such as {F}Ium at different times conveying specifically the "Principal axis" notion, the generic "Axis" parent notion, the "Vertical" mirror plane notion, as well as the notion of a generic mirror plane with no specified relation to a principal axis.

Table 2. Frequency table of gestural form codes overlapping with selected notions for participant Sp1.

Gestural form codes	Principal axis	Dihedral	Horizontal	Vertical	Mirror plane (Parent)	Cn Rotation (Parent)	Axis (Parent)
{F}Hfd	0	0	2	0	2	0	0
{F}Hmd	0	0	7	0	2	1	0
{F}Iaf	0	0	0	0	2	0	0
{F}Idb	0	1	0	1	2	0	0
{F}Ifm	0	0	0	5	14	0	0
{F}Imb	0	1	0	2	7	0	0
{F}Ium	3	0	0	5	4	0	1
{M}(Guu)Ta(Guu)	0	0	0	0	1	0	0
{M}Td(Ifm)	0	0	0	0	3	0	0
{M}Tf(Ium)(Ium)> Tb(Ium)(Ium)	0	0	0	0	1	0	0
{M}Tm(G12uu)(Ium)	0	0	0	0	1	0	0

{M}Tu(Ium)(Ium)> Td(Ium)Ium)	0	0	0	0	1	0	0
{M}R+x(2db)(Ifm)	0	0	0	0	1	0	0
{M}R-x(Hfd)	0	0	1	0	1	1	0
{M}R+z(Ifm)	0	0	0	0	2	0	0

The “Inversion”, “Rotation”, and the parent “Improper Rotation” codes were removed from this table as there were no gestural form codes which overlapped with those presented.

Figure 7. (Left) A gesture that was produced by Participant Sp1, where the hand is held parallel to the transverse plane of the body (“H”) with fingers forward (“f”) and palm down (“d”). There is no motion associated with this gesture (“{F}”). This is coded as {F}Hfd. (Middle) A gesture that was produced by Participant Sp1, where the hand is parallel to the medial plane (“I”) with fingers upward (“u”) and palm faced medially (“m”). There is no motion associated with this gesture (“{F}”). This is coded as {F}Ium. (Right) A gesture that was produced by Participant Sp1, where the hand is parallel to the medial plane (“I”) with fingers pointed forward (“f”) and palm faced medially (“m”). The hand also translates downward in the -z direction indicated by the white arrow (“{M}”Td”). This gesture is coded as {M}Td(Ifm).

It was occasionally necessary to return to the video recordings to understand seemingly irregular codes. For example, most of the gestures that participant Sp3 enacted when conveying the “Horizontal” mirror plane notion involved the “H” gestural form code. However, they enacted a gesture we coded as {F}Ifm when asked about a hypothetical gesture that would distinguish between σ_v and σ_h. They explained,

> *“You would have to first establish what the molecule-, where it is in three-dimensional space. If you have the molecule slanted, or perhaps on a different axis, then those planes would change. Because this (gesture) means vertical, diagonal, and horizontal at the same time if I didn’t specify where the molecule would be positioned.”*

RESULTS

Common Gestural Forms

As described in the methods, to address the forms gestures may take as stated in Research Question 1, we identified 218 unique gestural codes from our observations of the students. These are presented in full in the Supporting Information. From those, there were 180 gestural form codes observed to overlap with the 10 notions in our analytical framework. Tabulated gestural form-notion overlap is presented in the Supporting Information.

We have listed the twelve most common gestures, their most associated notions, and depictions of the gestural forms in Table 3. The most common gestures use either a flat hand shape that is oriented parallel to the transverse body plane (*i.e.*, using the "H" hand shape code) or perpendicular to that plane (*i.e.*, using the "I" hand shape code). Gestures using these hand shapes are predominantly associated with notions involving mirror planes, with the former often referring to horizontal mirror planes and the latter to vertical mirror planes.

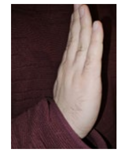
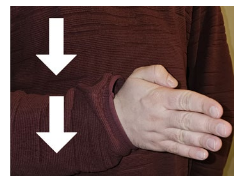
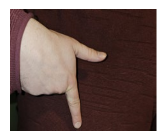
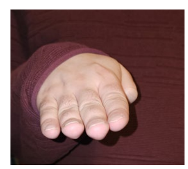
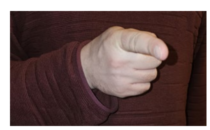
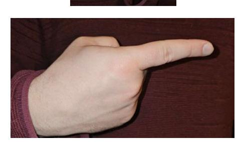
Interestingly, the "Ifm" gestural form, where a flat hand is oriented vertically with the fingers faced forward and palm faced medially, appears twice in Table 3; first in a stationary form as {F}Ifm and in a form involving a linear downward movement as {M}Td(Ifm). As both gestures have similar notion associations, we take this as evidence that the translational motion in the latter gesture is further emphasizing the critical gestural component; the flat hand embodying the plane.

There are also several gestural forms in Table 3 that invoke a hand shape where the index finger is pointed in some direction, *i.e.,* using the "2" hand shape code. The most common of these, {F}2db, has the index finger pointed downward while the palm is faced back toward the body of the speaker, and appears to invoke the unidimensionality of axes. Indeed, several participants directly confirmed this perspective during the interviews. Participant Sp1, for example, said, "… [T]o me, axes of rotation are more one-dimensional so I like to use a finger…". In a different interview, participant Fa2 recognized that fingers are literally three-dimensional objects but that a pointed finger "gets the point across", and that other analogues like a pencil might be used to physically represent an axis but that, "… it's the same as a finger in [Fa2's] mind." Similar confirmations occurred in every other interview except with participant Fa1.

Correlation of Gestural Features to Specific Notions

For Research Question 2 our analysis focuses on the notions expressed by students and the relationship those have to their gestures. Table 4 shows the frequency and spread of the 10 notions

Table 3. Most common gestures across participant interviews

Gestural Form code	Frequency	Most Common Notion	Depiction
{F}Ifm	43	Mirror plane (parent) (27/43)	
{F}Ium	32	Mirror plane (parent) (14/32)	
{F}Hmd	27	Horizontal mirror plane (13/27)	
{M}Td(Ifm)	26	Mirror plane (parent) (14/26)	
{F}Imb	24	Mirror plane (parent) (16/24)	
{F}2db	17	Axis (parent) (10/17)	
{F}Hfd	16	Mirror plane (parent) (8/16)	
{F}2fm	13	Axis (parent) (10/13)	
{F}2ub	13	Axis (parent) (8/13)	
{F}2mb	12	Axis (parent) (11/12)	
{F}2fd	11	Principal Axis (3/11) or Axis (parent) (3/11)	

{M}Td(Imb)	11	Vertical (6/11)	

which constitute our analytical framework throughout the seven interviews. The full table which includes the sixteen sub-notions is present in the Supporting Information. Every one of these notion codes is covered by at least five of our participants, except for the Improper Rotation parent code.

Table 4. Notion code counts by participant and in total.

Notion codes	*Sp1*	*Sp2*	*Sp3*	*Sp4*	*Sp5*	*Fa1*	*Fa2*	*Total*
Inversion	6	3	2	6	5	2	1	25
Principal Axis	17	0	3	6	7	0	5	38
Rotation	24	5	8	11	11	2	12	73
Dihedral	5	1	4	1	1	0	4	16
Horizontal	14	9	12	6	8	3	6	58
Vertical	23	13	5	10	11	0	7	69
Mirror Plane (parent)	44	11	25	14	30	6	8	138
Rotation (parent)	16	0	4	2	1	7	9	39
Axis (parent)	29	9	31	16	12	13	10	120
Improper Rotation (parent)	0	0	0	9	0	0	5	14
SUM	178	51	94	81	86	33	67	590

To address Research Question 2, we sought correlations between specific notions and components of gestures. Table 5 summarizes critical gestural components in gestural form-notion overlaps for all seven interview participants. To extract a “critical gestural component”, we required that the student use three or more unique gestural forms for that notion. Furthermore, the critical gestural components presented in Table 5 for a given notion had to account for at least 50% of the total overlaps with that notion for that individual. For example, participant Sp4’s heat map indicated they used five unique gestural forms to communicate the “Vertical” notion. Three of those gestural forms were used by Sp4 only once ({F}Imb, {F}Iub, and {F}Iuf) while another was used twice ({M}Td(Imb) and another five times ({F}Ium). We judged that the critical gestural component for Sp4 when engaging with the “Vertical” notion was {F}I--as that gestural form occurred in 80%, or 8 out of 10, instances when a gesture occurred.

Table 5. Critical Gestural Components by Notion for each Participant

	Sp1	Sp2	Sp3	Sp4	Sp5	Fa1	Fa2
Principal Axis	{F}2--	None (0)	None (2)	{F}2--	{M}Td(2--)	None (0)	None (1)
Axis*	{F}2--	{F}I-- {M}T-(I--)	{F}2-- {M}--(2--)	{F}2--	{F}2-- {M}Td(2--)	{M}T-(2--)	{F}2d- {M}T-(2d-)

Proper Rotation*	{M}R--(---)	None (0)	{F}2-- {M}--(2--)	None (2)	None (1)	{F}I-- {M}Td(I--)	{F}2--
Rotation	{M}R-z(---)	{M}R--	{M}R--	{M}R-(---)	{M}R-(--) {M}O-(--)	None (2)	{M}R-z(---)
Mirror Plane*	{F}I-- {F}H--	{F}I-- {M}T-(I--)	{F}H-- {F}I--	{F}H-- {F}I--	{F}I-- {M}T-(I--)	{F}I-- {M}Td(I--)	{F}I-- {F}H--
Horizontal	{F}H-d	{F}H-- {M}T-(H--)	{F}H-- {M}T-(H--)	{F}H--	{F}H-- {M}T-(H--)	{M}T-(-md)	{F}H-- {M}--(H--)
Vertical	{F}I--	{F}I-- {M}T-(I--)	{F}I-- {M}T-(I--)	{F}I--	{F}I-- {M}Td(I--)	None (1)	{F}I-- {M}T-(I--)
Dihedral	{F}I--	None (1)	{F}I--	None (1)	None (1)	None (0)	{F}I-- {M}T-(I--)
Improper Rotation*	None (0)	None (0)	None (0)	{M}--(---)	None (0)	None (1)	{M}--(2mm)
Inversion	{F}Gmm	None (2)	None (1)	{M}--(G--)--(G--)	{M}T-(Gmm) T-(Gmm)	None (2)	None (1)

Parent notions are denoted with an asterisk. Notions for which no critical gestural component was discerned are marked as "None" with the total number of unique gestures used by that participant to indicate that notion. A dash (-) is used as a wildcard in the gestural form syntax when a part of a gesture (*e.g.*, finger orientation) was not deemed critically important.

Several interesting trends emerge from this table. We coded the principal axis of rotation as a separate notion from generic axes because the principal axis is significant for defining mirror planes and point groups. Despite this, there are several similarities between the two notions. All three participants who consistently gestured the "principal axis" notion used their index finger, denoted in our coding scheme as "2"; the remaining four did not communicate this notion with sufficient frequency to enable analysis. Similarly, six out of the seven participants used their index finger to indicate a generic axis with the "axis" parent notion. We interpret this as strong evidence that the index finger can serve as an embodied analogy of an axis. Conversations during interviews also clarified that gestures using the index finger to communicate notions about axes, using forms such as {F}2db in Table 3, were *not* deictic; participants were not pointing *to* the axis but were having their finger *embody* the axis.

There were also often similarities between the "Rotation" notion, used when the participant was indicating a generic rotation, and notions indicating rotations with specified angles (*i.e.*, those with the "Proper Rotation" parent code). The critical feature for most participants for rotation notions was that some part of the hand rotated, though participants Sp1 and Fa2 did typically gesture with rotations specifically along the z-axis. Participant Sp3 emphasized the pointed index finger ({F}2-- and {M}--(2--))

for both the “Proper Rotation” parent code and “Axis” parent code. This could imply that instances where Sp3 was discussing rotations, they were doing so mentally while physically embodying the axis by which they did the rotation.

For most individuals, differentiating between the horizontal and vertical mirror planes involves a planar hand shape that is parallel and perpendicular to the transverse plane of the body, respectively. Indeed, both hand shape codes appear as dominant features for nearly all participants when indicating a generic mirror plane as seen in the “mirror plane” parent notion. Participant Fa1 deviated interestingly when communicating the “horizontal” notion, however, as the critical gestural component was a translation of the hand where the finger(s) were pointed medially and the palm was faced down, as if they were using their hand to trace the plane regardless of the shape their hand took.

We note that the “dihedral” plane notion was indicated less often not only because of the scarcity of dihedral planes in the molecules studied but also because they are treated as functionally identical to vertical mirror planes in all instances of undergraduate inorganic chemistry at this institution; thus, when dihedral planes appeared in the course they were simply referred to as vertical planes.

Participants Rarely Gestured about Improper Rotations and Inversions

Improper rotations and inversions (which are S2 rotations) were discussed far less often by participants than the C_n and σ operation classes. Participants seemed less likely to gesture about improper rotation and inversion operations even when they were brought up in conversation, leading to a smaller sampling for these notions as seen in Tables 4 and 5. There are several possibilities for why these notions may be undersampled. For one, there are indications elsewhere in the literature that students have difficulties with these operations.[7,13,14,15,49] Thus, participants may be gesturing about these operations and elements less frequently because their underlying conception is uncertain. It is for this reason alone that we elected to present data regarding the “Inversion” and “Improper Rotation” notions in Tables 4 and 5 despite undersampling. A review of the instructional material given to the participants in their respective inorganic chemistry courses indicates instructors did value knowledge of these operations. Both operations appeared in lecture materials, homework, exam materials, and in the symmetry and group theory model-building activity given to students during their laboratory course component. However, identifying these symmetry elements is not necessary when determining molecular point groups using common flowcharts[50] and so they be implicitly deemphasized as students progress through the course. Furthermore, improper rotations are typically described as two operations in one; a proper rotation followed by a reflection in the perpendicular plane. It is possible that this composite nature renders these symmetry elements too complex for individuals still learning the material to consistently gesture.

Evidence of a Zipfian Distribution in Gestural Forms Used

Of the 180 unique gestural forms in our data, 85 of them only occurred once while an additional 47 occurred twice. That is, 73.3% of the observed gestural forms accounted for only 30.3% of gestural form-notion overlaps. In contrast, the 18 most common gestural forms, only 10% of all unique forms, accounted for 49.8% of overlaps. Analysis presented in the Supporting Information indicates that the gestural forms used in this environment follow a Zipfian distribution. Similar distributions have been observed in many languages such as English.[51]

DISCUSSION

From an embodied cognition perspective, our data (especially Tables 3 and 5) might suggest that our physical experience can both support *and* hinder student understanding of symmetry and group theory concepts. This is most plausible when considering the link between the "Horizontal" plane notion and flat-handed gestures with orientations parallel to the transverse plane (*e.g.*, with the "H" orientation code) and "Vertical" plane notions with gestures that have flat hand orientations in the coronal or frontal planes (*e.g.*, with the "I" orientation code).

That gestures with the "H" orientation code are often associated with the "Horizontal" notion is unsurprising as we perceive the horizon as splitting the sky above from the earth below. Thus, a horizontally oriented gestural form, such as {F}Hmd or {F}Hfd in Table 3, would split a compound into top and bottom halves. Simlarly, our own physical verticality involves the z-axis of the body and planar gestures using the z-axis would thus be inherently vertical. Unfortunately, these rationalizations stemming from embodied experiences are problematic considering the proper mathematical definition of the horizontal and vertical mirror planes. Horizontal planes must be perpendicular to the principal axis of rotation. Thus, a hypothetical compound's horizontal mirror plane would not be aligned with the horizon if its principal axis was not coincident with the z-axis of the body (see Figure 8). This creates a contradiction wherein a horizontally-aligned gesture does not coincide with a mathematically defined horizontal mirror plane. This contradiction has been observed several times over multiple semesters wherein students insist that a given mirror plane is defined as horizontal or vertical based on their perspective, which becomes embodied as they gesture. Similarly, as vertical mirror planes must be coincident with the principal axis of rotation, non-conventional orientations such as the one seen in Figure 8 would pose a similar issue. Thus, when gesture functions successfully as an analogy then productive understanding might be enhanced (*e.g.*, hands as planes and fingers as axes) and when the analogy breaks, conception might be hampered (*e.g.*, horizontal planes not aligning with the horizon/transverse plane of the body).

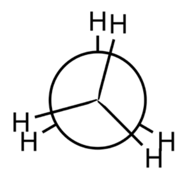


Figure 8. Newman projection of eclipsed ethane where the principal axis is coming out of the page. Thus, the horizontal mirror plane is the plane of the page and runs counter to embodied intuition that the horizontal mirror plane must be oriented with the horizon.

CONCLUSIONS

Implications for Instruction

There is copious evidence that gesture is an efficacious communicative medium[27,28,33], including in educational environments.[21-26,30-32] We suggest the reader actively consider how they use gesture when they communicate, whether that be as scholars at conferences or as instructors in classrooms. We have several suggestions for using gesture in symmetry and group theory instruction based on our data. While Table 5 implies that planar hand shapes parallel to the transverse body plane typically convey the notion of a horizontal mirror plane (and planar hand shapes that are *not* parallel to that plane as implying vertical mirror planes), Table 3 further indicates that certain gestures may have better communicative power based on the argument that they were used more often. For gestures implying vertical planes specifically, using a flat hand with palm faced medially and fingers pointed either forward or upward (that is, {F}Ifm and {F}Ium, respectively) may be best. Keeping one's hand flat with palm faced down and fingers faced medially (*i.e.*, {F}Hmd) may be effective for communicating horizontal mirror planes, with a reasonable alternative changing the orientation of the fingers from medial to forward (*i.e.*, {F}Hfd). Similarly, there is evidence in these tables that the index finger is uniquely useful for embodying axes, with Table 3 indicating that having the finger pointed downward with the palm back towards the speaker may be particularly useful.

It is more difficult to suggest gestural forms to employ when discussing notions that were undersampled here, such as the improper rotation and inversion notions. If the underlying cause for the comparative dearth of gesturing is the difficulty of these specific concepts then learning may be supported by the deliberate incorporation of gestures during instruction followed by observation of how students employ and/or modify those gestures. In this way, the meaning of gestures becomes co-constructed to the benefit of both the instructor and students.[21] For improper rotations, we might suggest using the index finger of one hand to indicate the improper rotation axis while keeping the other hand flat and oriented perpendicular to the other hand's index finger to embody the perpendicular mirror plane. In other words, we might suggest using either {F}(2db)(Hmd) or {F}(2db)(Hmu) depicted in Figure 9.

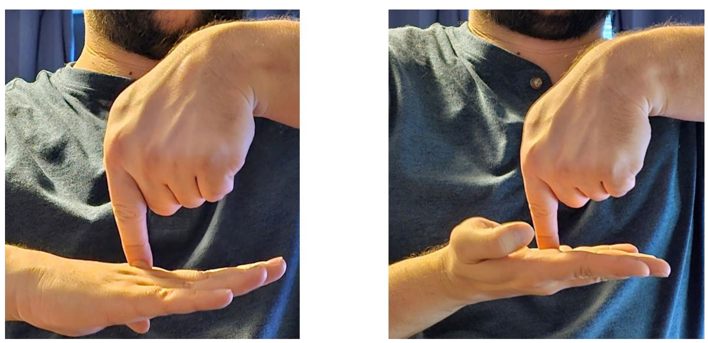


Figure 9. Proposed gestures for indicating improper rotations. On the left is {F}(2db)(Hmd) and on the right is {F}(2db)(Hmu).

Regardless, this work and others[21,22,30] supports providing students with opportunities to explore chemistry concepts not only through words but also through bodily engagement. Though encouraging gesture was not an intentional design principle, activities like our previously published work[13] provide opportunities for students to engage with the material in this manner and we would encourage practitioners to watch for or encourage gestures in recitation periods, "dry" laboratory experiments, lectures, or anywhere else where discussion may occur.

Implications for research

The data here shows the degree to which gestural forms may vary, even in the limited context explored here. This breadth could be posed as a potential challenge for effective pedagogy. In the same way that we choose our words carefully with the intent of communicating specific notions, it's reasonable to expect that a degree of similarity in gestural form might enhance communicative efficacy. This raises the question as to how we might guide students toward the use of *specific* gestural forms for the productive conception of ideas (if that is feasible to begin with). While the gesture literature supports that instructors use their own gestures in typical classroom environments, might we enhance the efficacy of those gestures through the investigation and development of specific principles regarding their use? Indeed, we are pursuing the purposeful development of gestures which convey the "improper rotation" and "inversion" notions considering our data shows these notions as particularly undersampled.

We recognize that the use of gesture in chemistry settings is of interest to the community based on various investigations that have appeared in the literature.[21,22,52] Investigating productive gestural mimicry may have been possible before the publication of this work but we hope that our gesture coding scheme might catalyze that or other gesture-based investigations. We encourage the community to use, develop, and discuss our gesture coding scheme and welcome any collaboration or discussion that may arise. Fascinating work has been done in organic chemistry that demonstrated a signed lexicon can have an impact on summative assessments.[53] Our coding scheme can extend similar work at institutions where the resources to develop a sign language lexicon may not be available or where interesting spontaneous gestures have been observed. Relatedly, our work might be used as a framework by which concepts, such as molecular structure, are communicated across courses (VSEPR in general chemistry, absolute configuration in organic chemistry, symmetry and group theory in inorganic chemistry, etc.).

LIMITATIONS

We recognize that the claims and gestures discussed here may not be generalizable to other inorganic chemistry classrooms or classrooms of other subdisciplines of chemistry such as organic chemistry.[53] Gestures are enacted by individuals who are influenced by their culture and the local social context.[54, 55] As such, we anticipate that there may be differences in gestural form across different boundaries, whether they be academic, cultural, geographic, and so on.

Though there is a literature basis in chemical education for the utility of gesture, we did not collect evidence that gesture affected student performance here. Indeed, there are demonstrable differences in gestural frequency and form between students as seen in our data but at most we have data indicating a general perception that gesturing was useful to students. A quantitative study analyzing student performance and gestural frequency and/or form might be of value and interest to the community, and we welcome collaboration in this endeavor.

Regarding the gesture coding scheme, the current iteration does have some shortcomings with respect to the immense detail it can capture. For example, we recognize that we cannot capture information on *where* a gesture is enacted. Assuming identical social circumstances, might a vertically aligned hand with fingers faced forward and palm faced medially (*i.e.*, {F}Ifm) enacted in front of one's chest at the midsagittal plane express a different notion, however marginally different, compared to the same gesture enacted at the hip or in front of the face? Though our analysis did not suggest that detail as relevant, we cannot rule out the possibility. Furthermore, the orientations of the fingers and palm are currently limited to 6 descriptors, but what if the gesture was oriented between two perpendicular descriptors? For example, not forward (+x axis) or medial (-y axis) but in between them? We considered treating the gesture as existing at the origin and then describing its orientation as pointing towards an octant. This would have resulted in us adopting a scheme by which we would describe orientation with a positive or negative designation for each axis such that, as an example, a gesture with the description [+,-,+] would have an orientation in the positive x- and z-axes but negative y-axis. We elected to not further complicate the system at this time and welcome the community's feedback.

Finally, though the gesture coding scheme has been used for data across multiple semesters and instructors, it has only analyzed gestures for one specific topic in one specific course. For the gesture coding scheme to demonstrate its full power (or evolve to overcome other shortcomings not apparent in this specific context), we encourage others to consider the applicability and feasibility of this scheme when gesturing about topics in other courses.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.XXXXXXX.

File containing the gesture coding scheme abbreviations, interview protocol, and codebook of notions (DOCX).

File containing the gestural form-notion heat maps, Zipf-related data, and full gestural form-notion overlap data (XLSX).

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J.J.M.: conceptualization, data curation, formal analysis, investigation, methodology, project administration, resources, validation, visualization, writing – original draft, writing – review & editing. D.J.W.: conceptualization, funding acquisition, resources, supervision, visualization, writing – review & editing. All authors have read and agreed to the published version of the manuscript.

CONFLICTS OF INTEREST

There are no conflicts to declare.

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